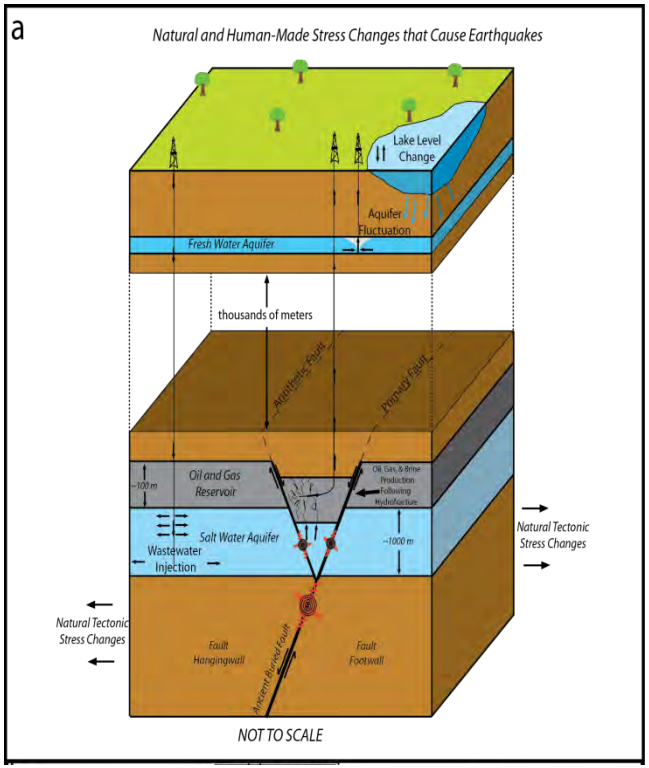
Overview of Induced Seismicity

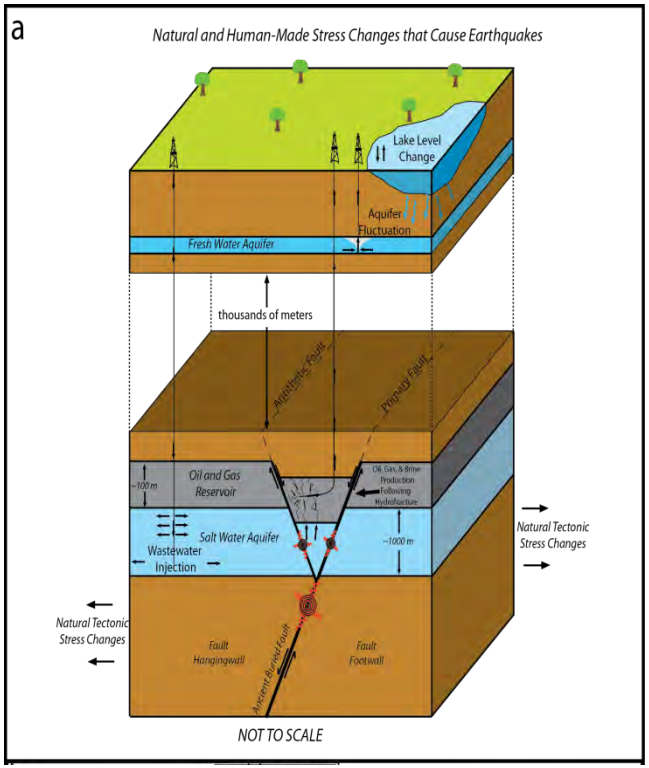
William L. Ellsworth
U. S. Geological Survey



USGS
science for a changing world

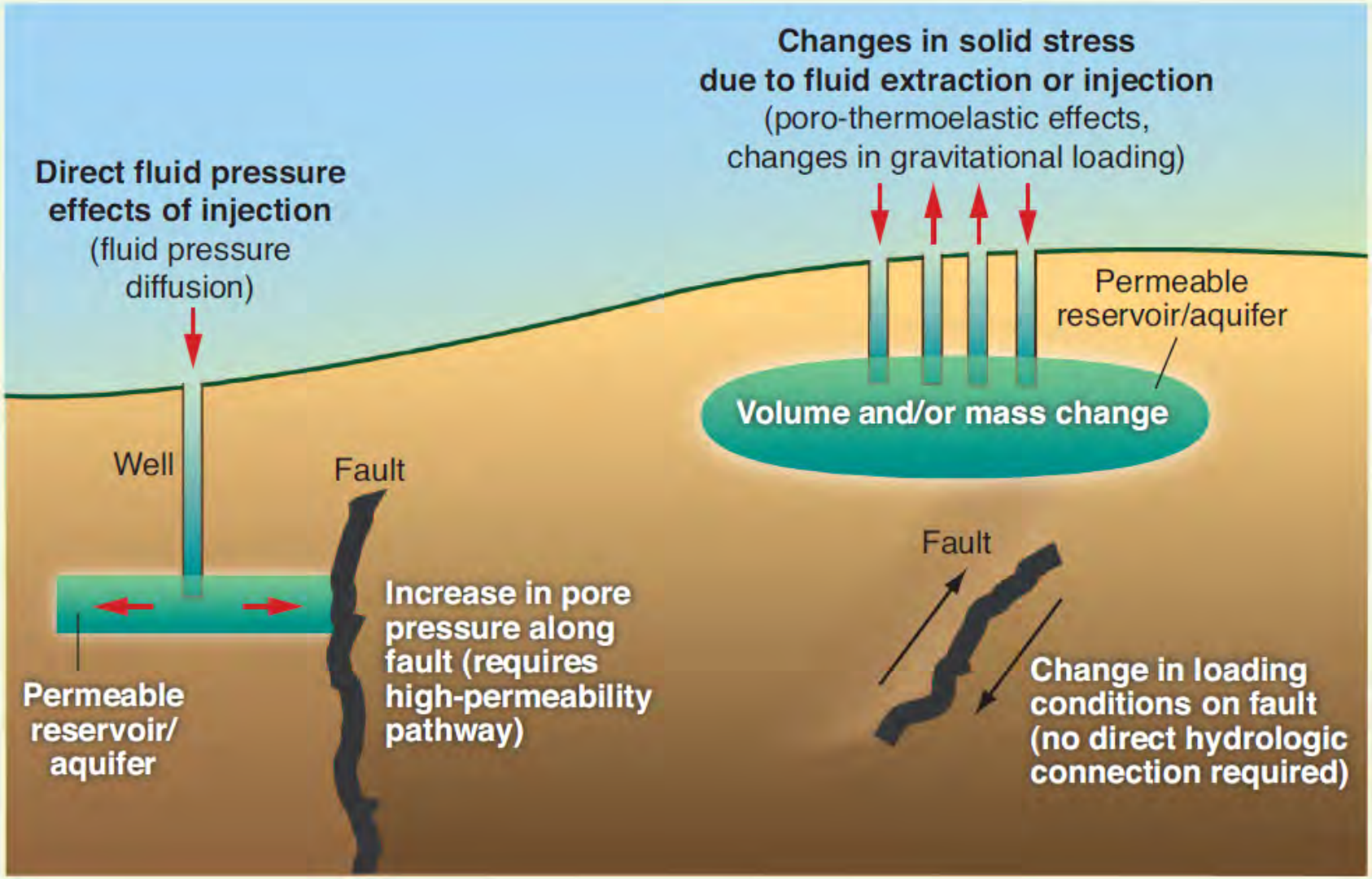
Outline

- Mechanics of induced earthquakes
- Increased earthquake activity in the U.S. midcontinent



USGS
science for a changing world

Mechanics of Induced Earthquakes



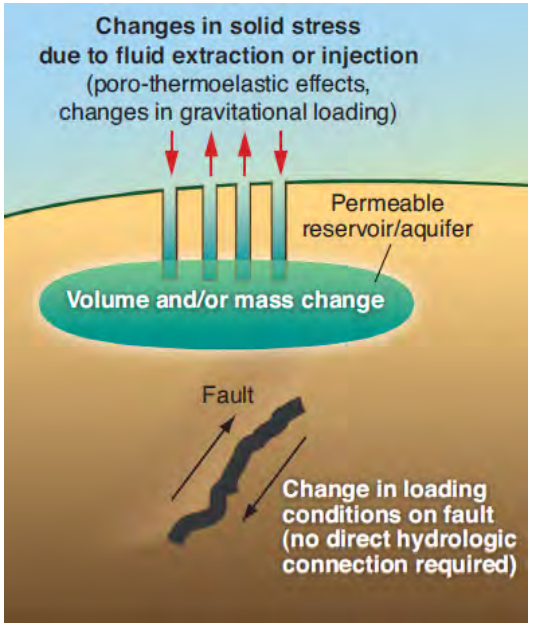
Mechanics of Induced Earthquakes: Solid Stress Effect

Bulletin of the Seismological Society of America, Vol. 76, No. 4, pp. 939–948, August 1986

THE EVOLUTION OF SEISMIC BARRIERS AND ASPERITIES CAUSED BY THE DEPRESSURING OF FAULT PLANES IN OIL AND GAS FIELDS OF SOUTH TEXAS

BY WAYNE D. PENNINGTON*, SCOTT D. DAVIS, STEVEN M. CARLSON†, JAMES DUPREE‡, AND THOMAS E. EWING§

The earthquakes in the Fashing and Pleasanton areas of South Texas are due to the withdrawal of fluids from the Fashing gas field and the Imogene oil field.



Bulletin of the Seismological Society of America, Vol. 85, No. 6, pp. 1888–1895, December 1995

The 9 April 1993 Earthquake in South-Central Texas: Was It Induced by Fluid Withdrawal?

by Scott D. Davis, Paul A. Nyffenegger, and Cliff Frohlich

The available evidence strongly suggests that the Fashing, Pleasanton, and Falls City earthquakes were all triggered by hydrocarbon production (Pennington *et al.*, 1986; Olson and Frohlich, 1992).

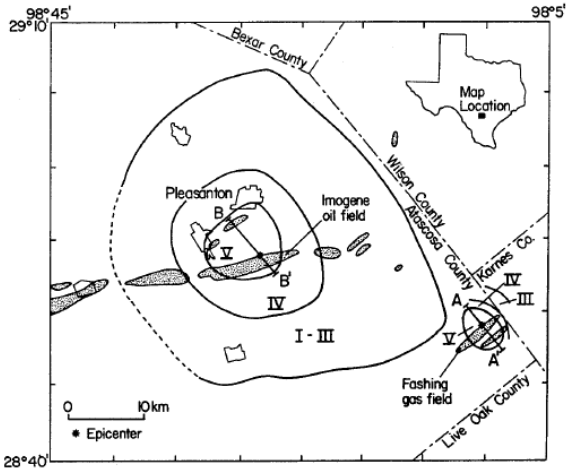
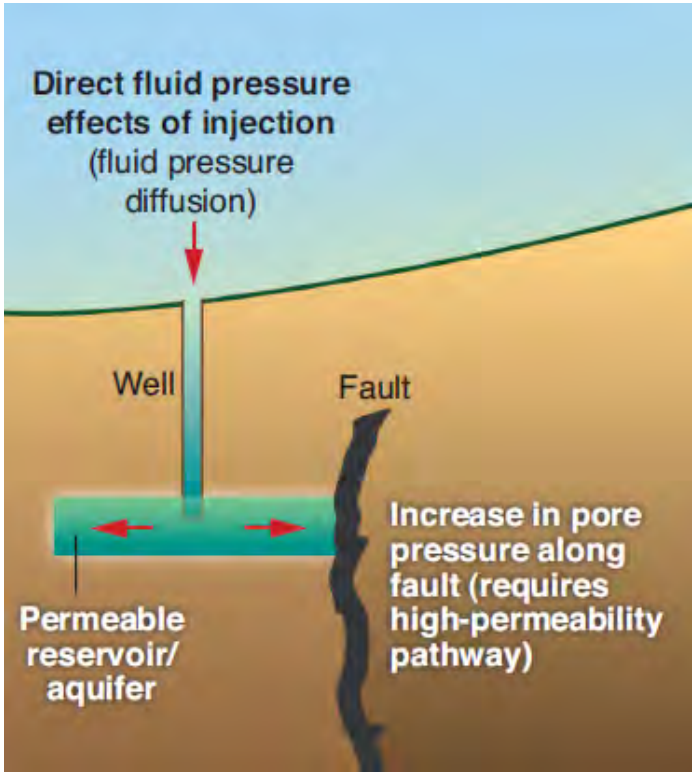


FIG. 1. Map of area in South Texas containing induced earthquakes. *Shaded* regions are more prominent oil and gas fields. Isoseismals for largest events are indicated in Modified Mercalli intensity scale. Locations of cross-sections in Figure 2 are indicated.

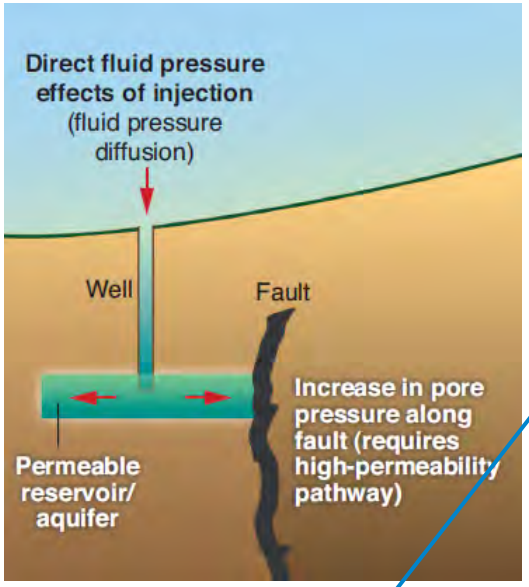
Mechanics of Induced Earthquakes: Pore Pressure Effect

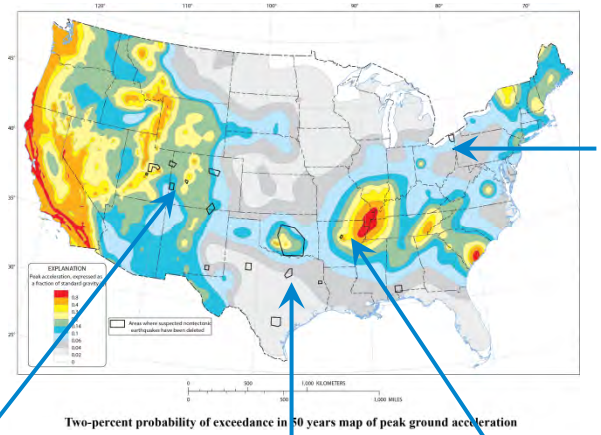


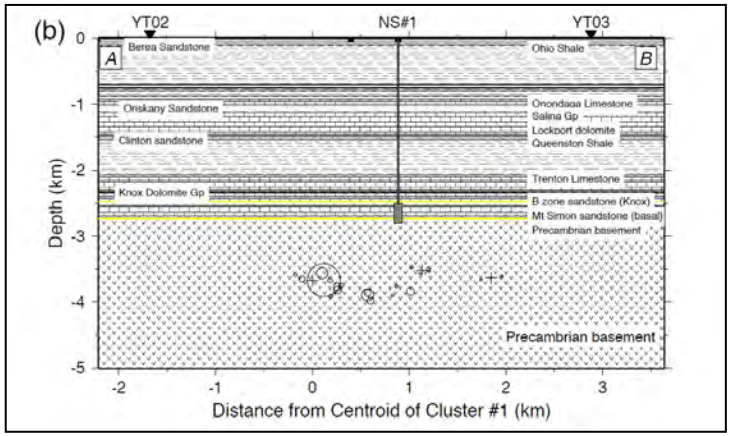
- Ancient faults can be reactivated by decreasing the effective normal stress

$$\tau\downarrow crit = \mu\,(\sigma n - P)$$

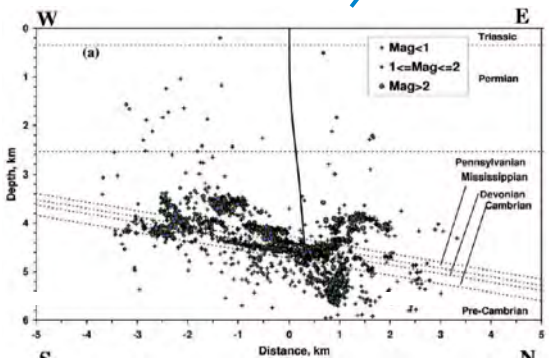
- Faults occur on a wide variety of scales and are found in virtually every geologic setting
- The Earth's crust is in a near critical failure state everywhere



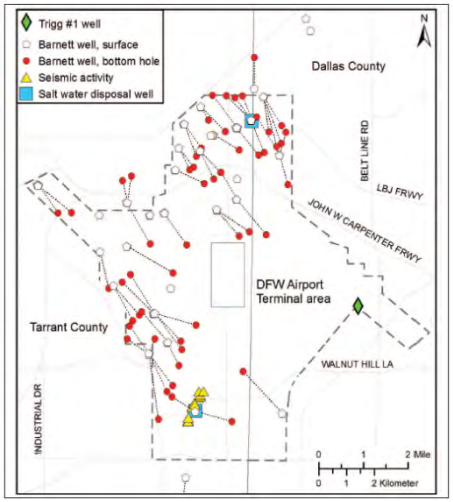




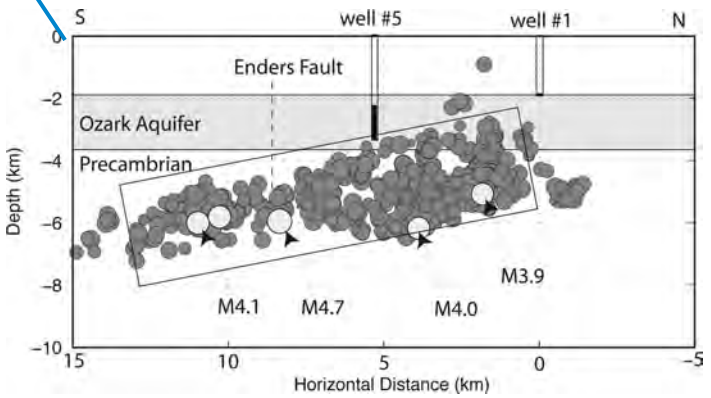
W.-Y. Kim, Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio. J. Geophys. Res. 10.1002/jgrb.50247 (2013)



Ake, J., Mahrer, K., O'Connell, D., and Block, L., 2005, Deep-Injection and Closely Monitored Induced Seismicity at Paradox Valley, Colorado. *Bull. Seismol. Soc. Am*, v. 95, 664-683.



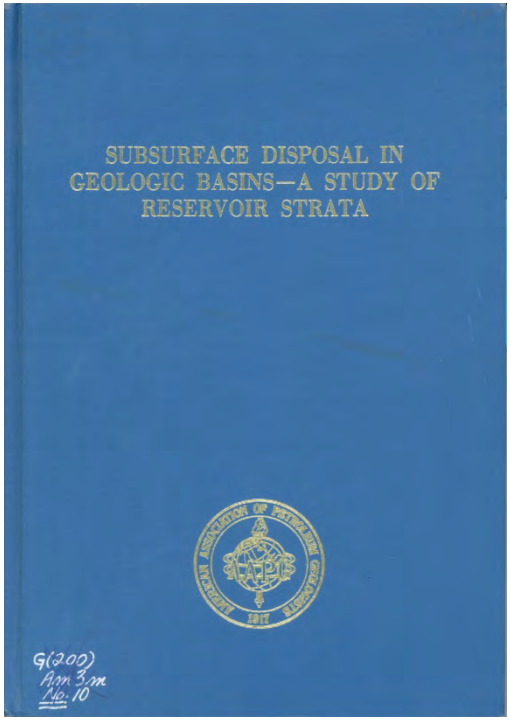
Frohlich, C., Hayward, C, Stump, B. and Potter, E., 2011, *The Dallas-Fort Worth Earthquake Sequence: October 2008 through May 2009*, Bull. Seismol Soc. Am, v. 101, 327-340.



Horton, S., 2012, *Disposal of Hydrofracking Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damaging Earthquake; Seismological Research Letters*, v. 83.

Mechanics of Induced Earthquakes
These are not new ideas

Subsurface Disposal in Geologic Basins – A study of Reservoir Strata
AAPG Monograph 10 (1968)



"the tremors … being the results of the release of stress when the pressures produced by injection of fluid overcome the friction on opposing rock surfaces."

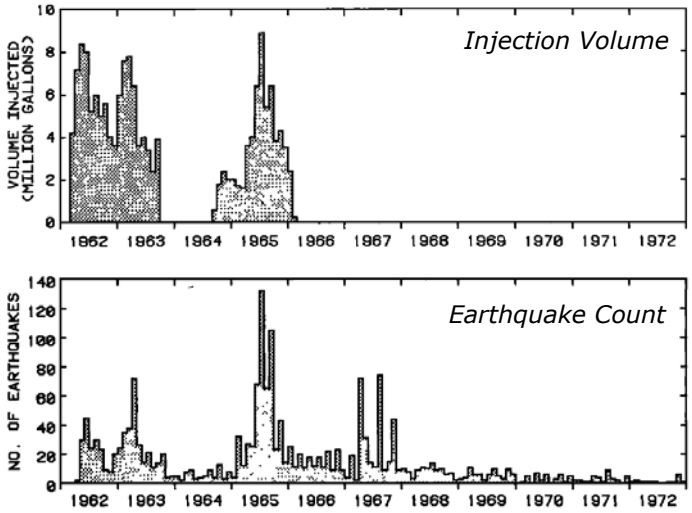
Underground Waste Management and Environmental Implications
AAPG Monograph 18 (1976)

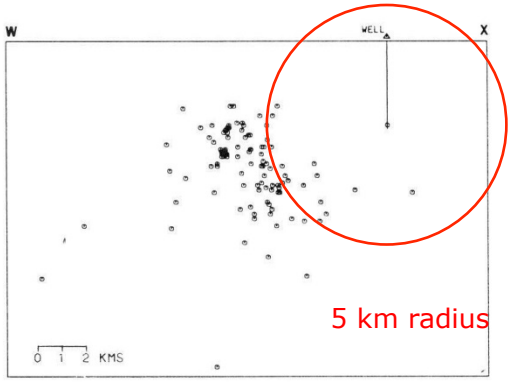
"The Denver earthquakes – and similar, less intensively studied cases in oilfields in western Colorado, Texas and Utah – have served a very good purpose in alerting us to this kind of long-term danger."

Denver Earthquakes

"The disposal of waste fluids by injection into a deep well has triggered earthquakes near Denver, Colorado."

Healy, J.H., Rubey, W.W., Griggs, D.T. and Raleigh, C.B., 1968, *The Denver Earthquakes; Science,* v. 161, p. 1301-1310.

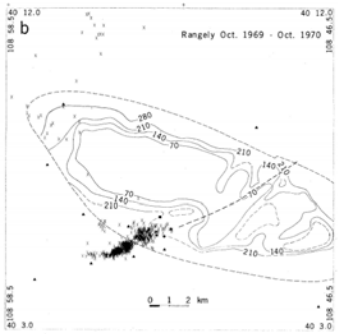




Earthquakes in 1967

Key Findings:

- Release of long-stored tectonic stress on ancient faults
- Earthquakes occurred more than 10 km from injection point
- Largest earthquake (Mw 4.8) occurred over one year after injection stopped
- Earthquakes continued into the 1980s

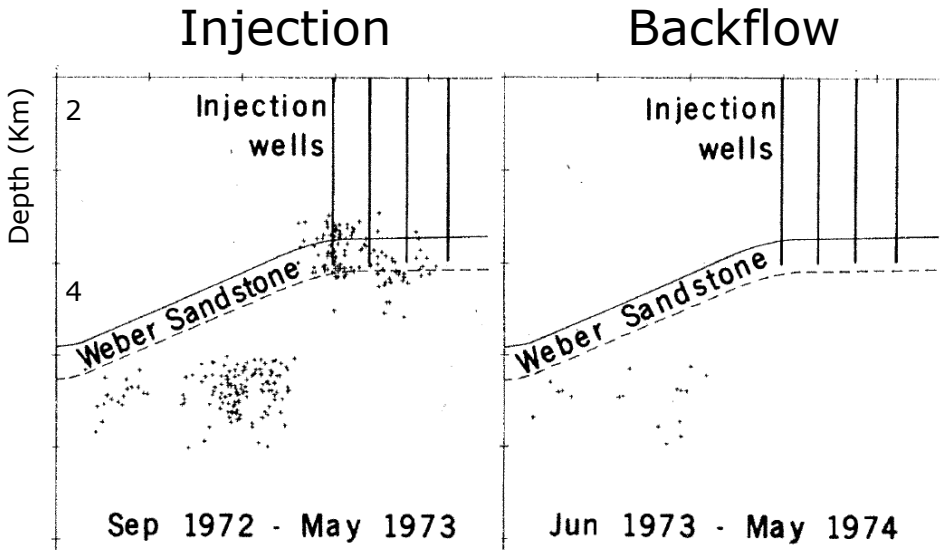


A Test of the Effective Stress Hypothesis at Rangely, Colorado

USGS experiment turned-on and off earthquakes in a Colorado oil field by varying injection pressure.

State of stress and pore pressure were measured, as was the frictional strength of the rocks.

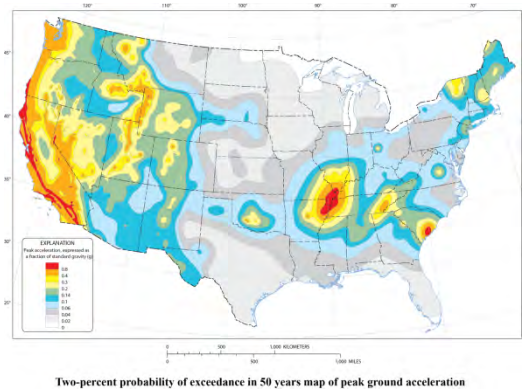
$$\tau\downarrow crit = \mu(\sigma n - P)$$



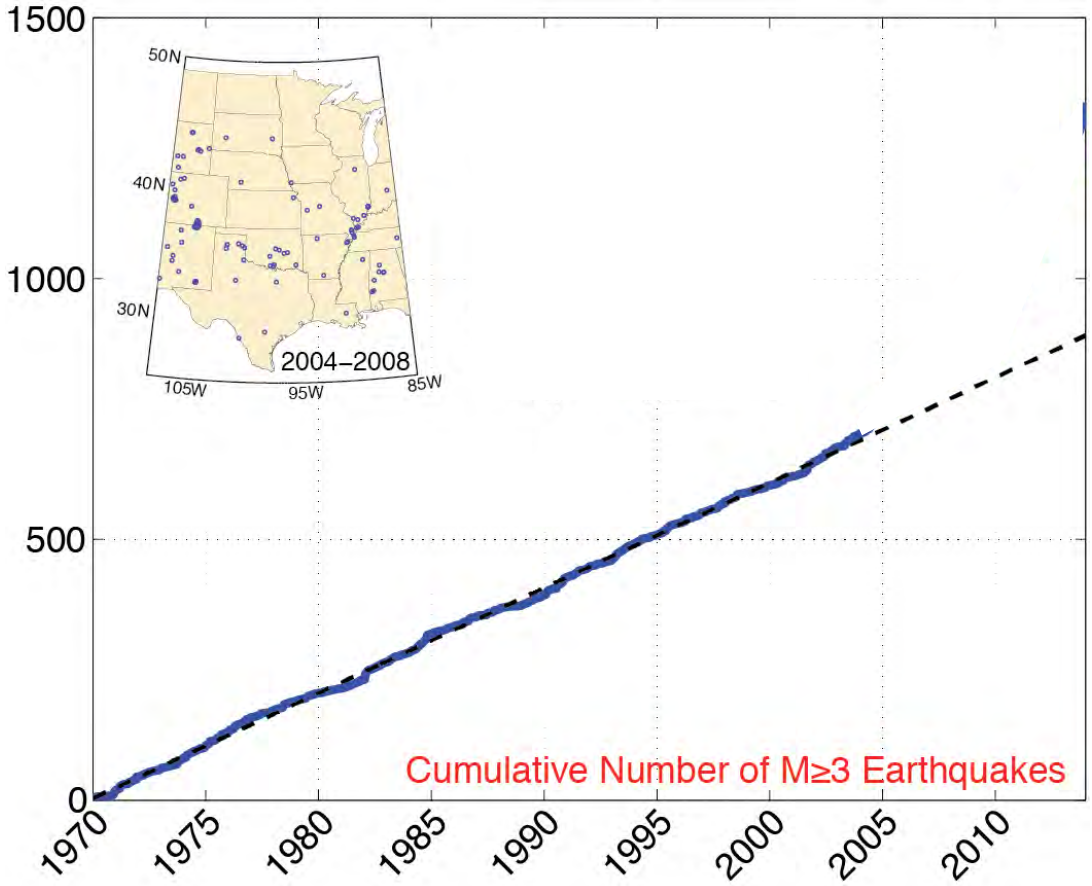
"The cessation of seismic activity within 1 day of the initiation of backflow in the experimental wells in May 1973 established the correlation between fluid pressure and earthquakes beyond a reasonable doubt."

Raleigh, C.B., Healy, J.H. and Bredehoeft, J.T, 1976, *An Experiment in Earthquake Control at Rangely, Colorado; Science,* v. 191, p. 1230-1237.

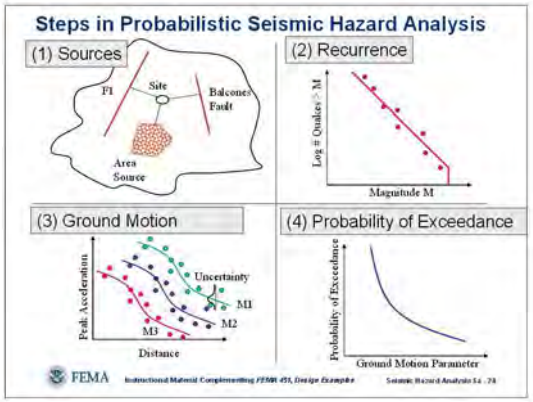
Hazard model for the central and eastern U. S. primarily based on past seismicity



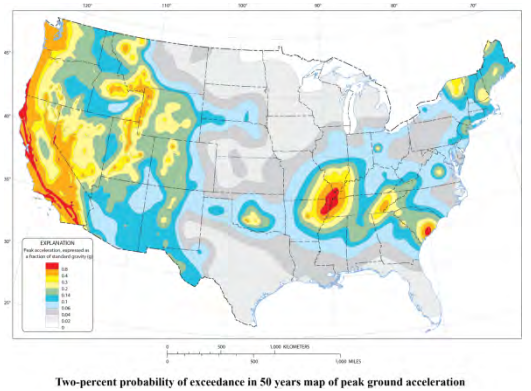
Two-percent probability of exceedance in 50 years map of peak ground acceleration



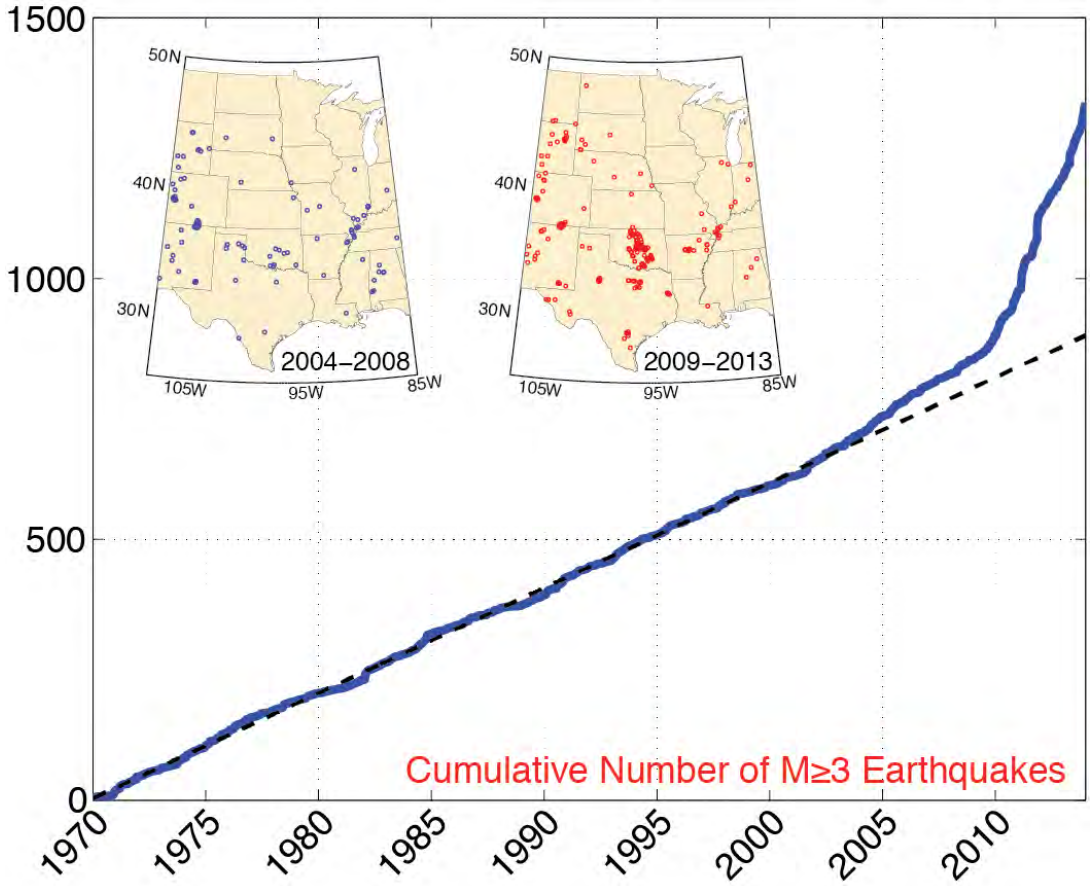
What rate of earthquakes should be expected in the future?



Hazard model for the central and eastern U. S. primarily based on past seismicity



Two-percent probability of exceedance in 50 years map of peak ground acceleration

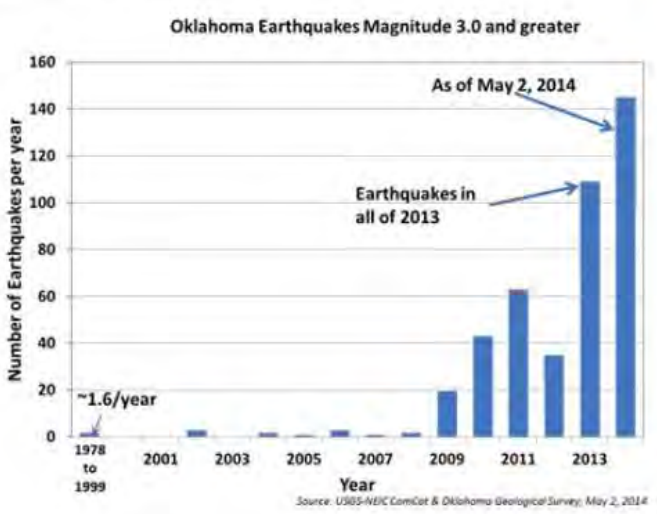


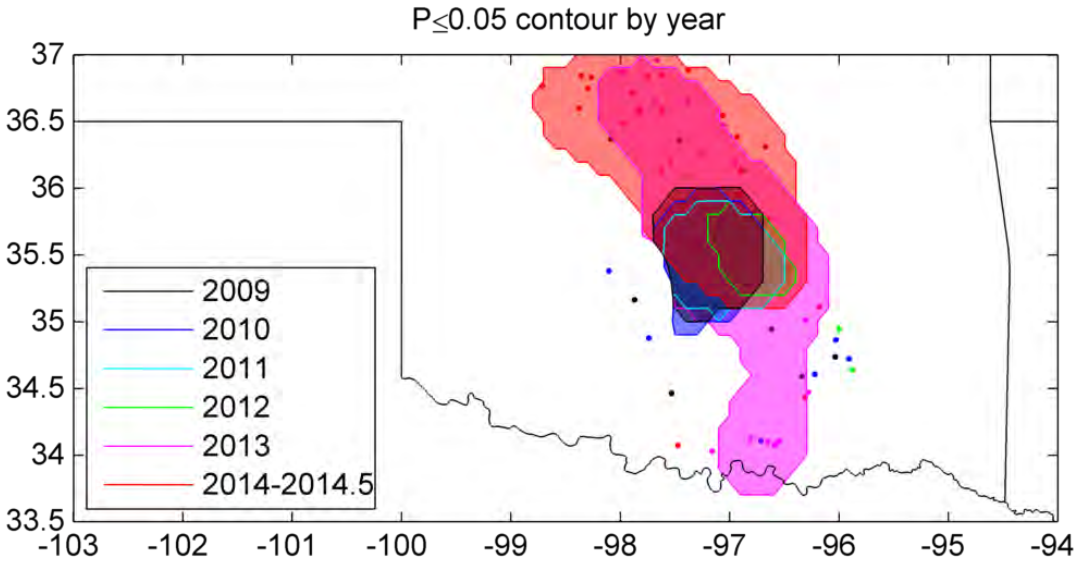
Higher rate of earthquakes implies higher hazard.

But how much higher?

And where has the hazard increased?

Increased Earthquake Activity in Oklahoma 2009-2014

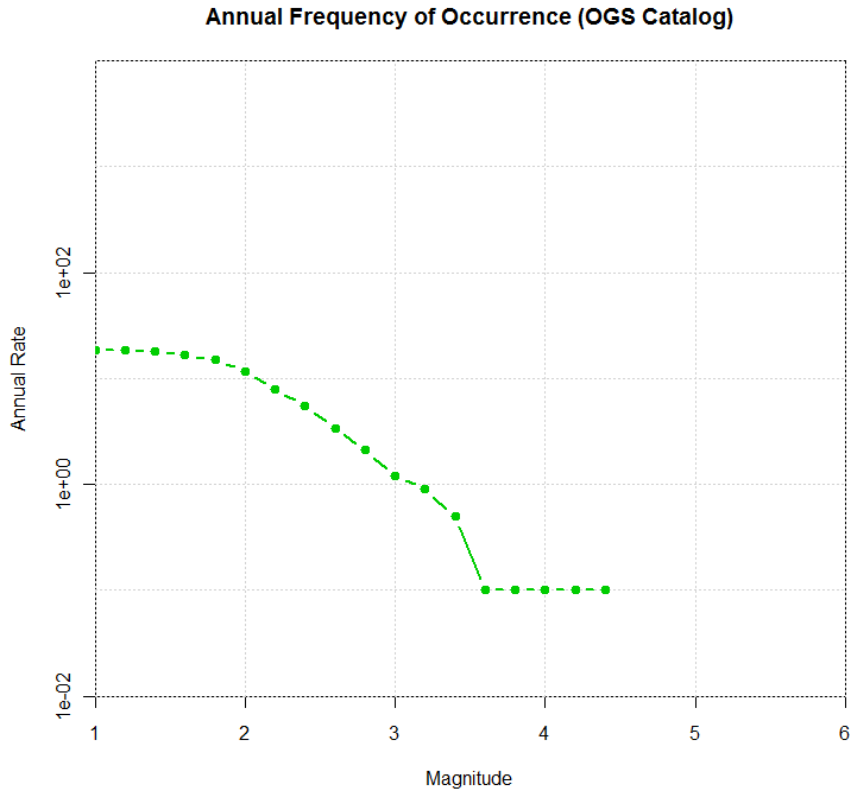


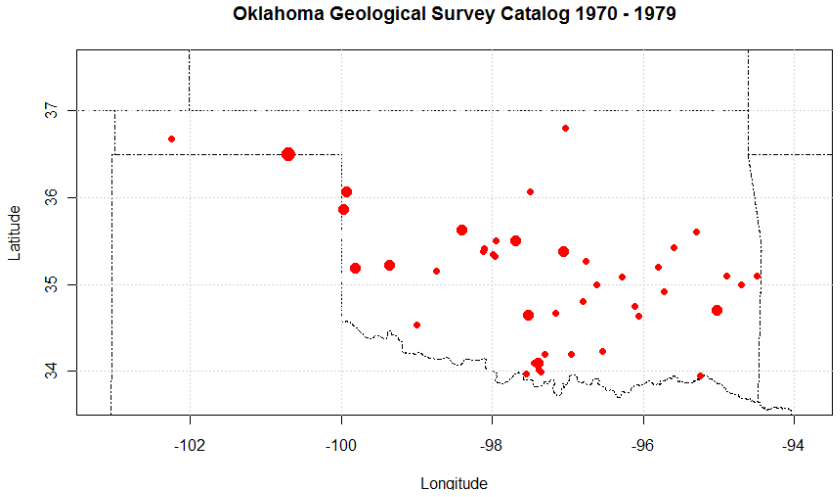


Regions with statistically significant increases in seismicity compared to historical activity

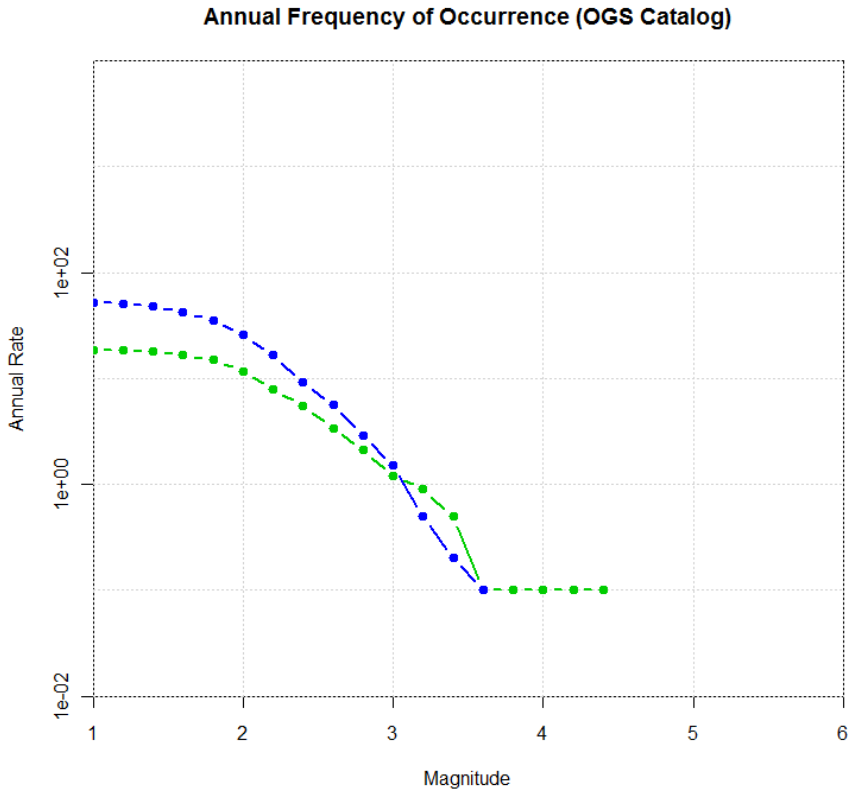
The earthquake rate in north-central Oklahoma (and southern Kansas) increase follows the drilling front by about one year

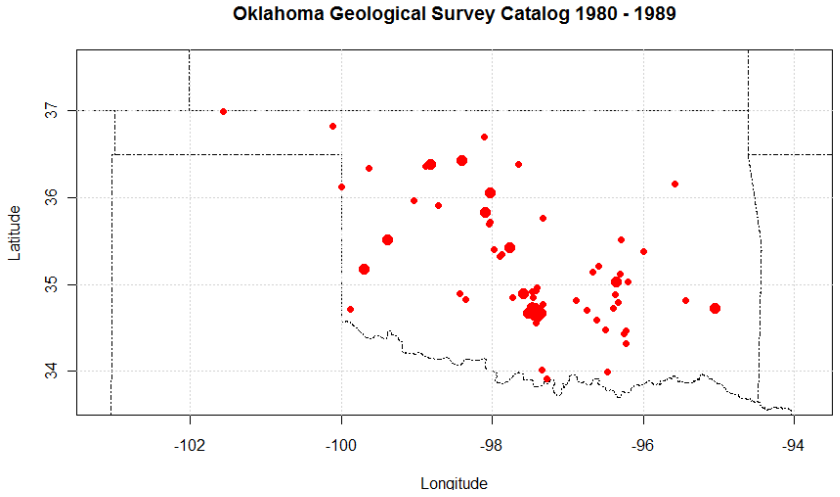
1970 - 1979


Annual Frequency of Occurrence (OGS Catalog)
Annual Rate
1e+02
1e+00
1e-02
1
2
3
4
5
6
Magnitude


Oklahoma Geological Survey Catalog 1970 - 1979
Latitude
37
36
35
34
-102
-100
-98
-96
-94
Longitude

1980 - 1989


Annual Frequency of Occurrence (OGS Catalog)
Annual Rate
1e+02
1e+00
1e-02
1
2
3
4
5
6
Magnitude


Oklahoma Geological Survey Catalog 1980 - 1989
Latitude
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-102
-100
-98
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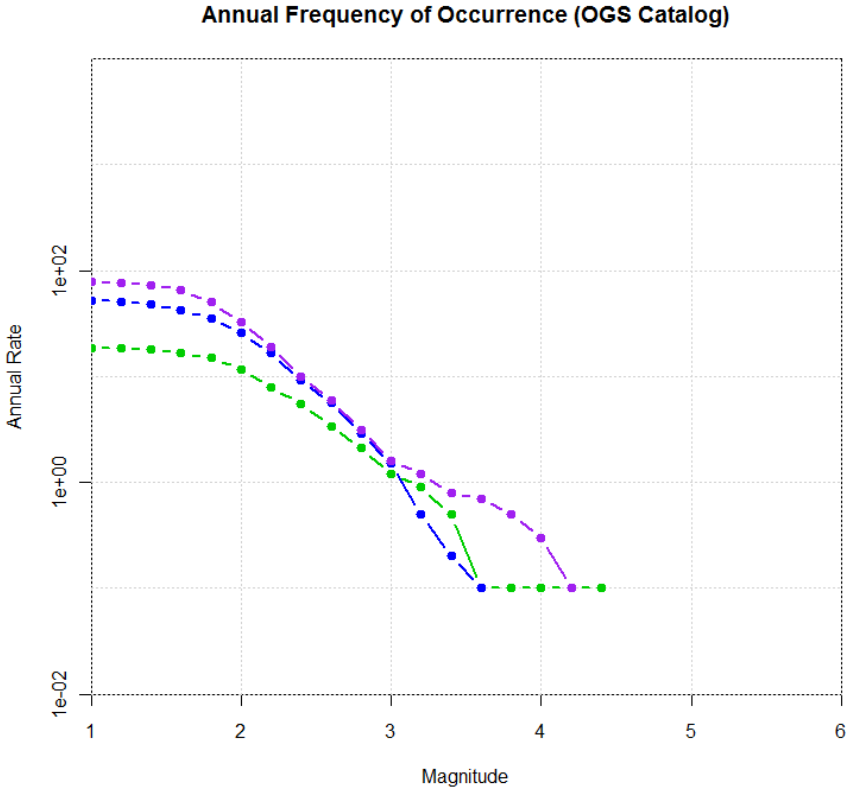
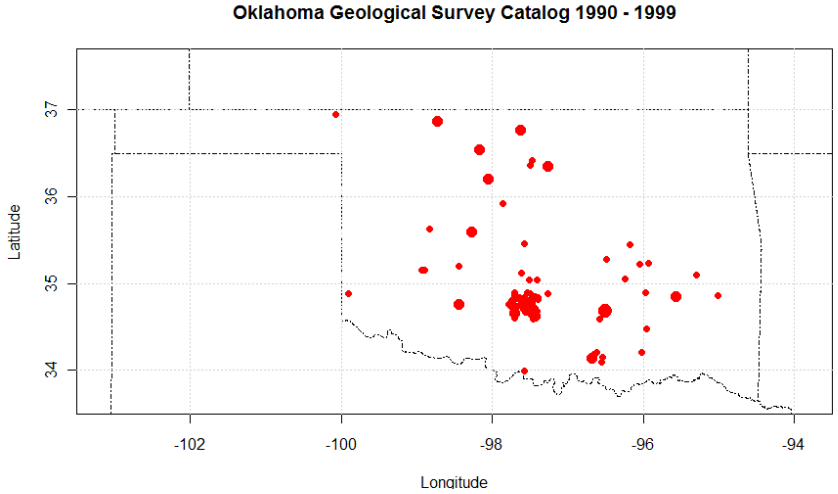
-94
Longitude

1990 - 1999


Annual Frequency of Occurrence (OGS Catalog)
Annual Rate
1e+02
1e+00
1e-02
1
2
3
4
5
6
Magnitude


Oklahoma Geological Survey Catalog 1990 - 1999
Latitude
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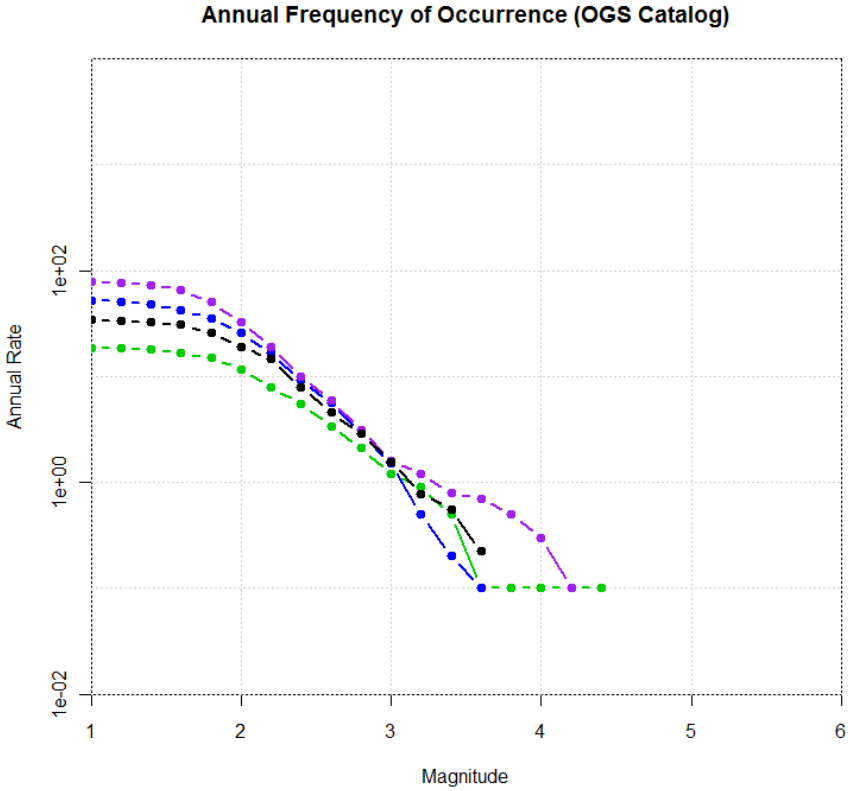
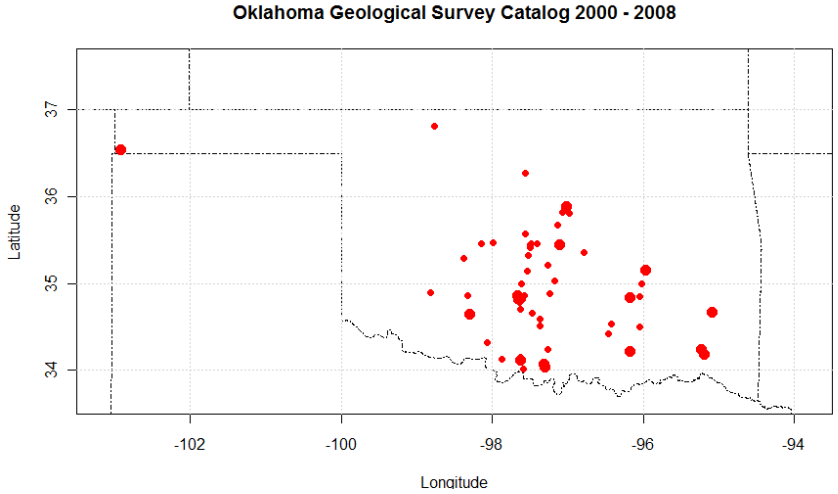
-96
-94
Longitude

2000 - 2008


Annual Frequency of Occurrence (OGS Catalog)
Annual Rate
1e+02
1e+00
1e-02
1
2
3
4
5
6
Magnitude


Oklahoma Geological Survey Catalog 2000 - 2008
Latitude
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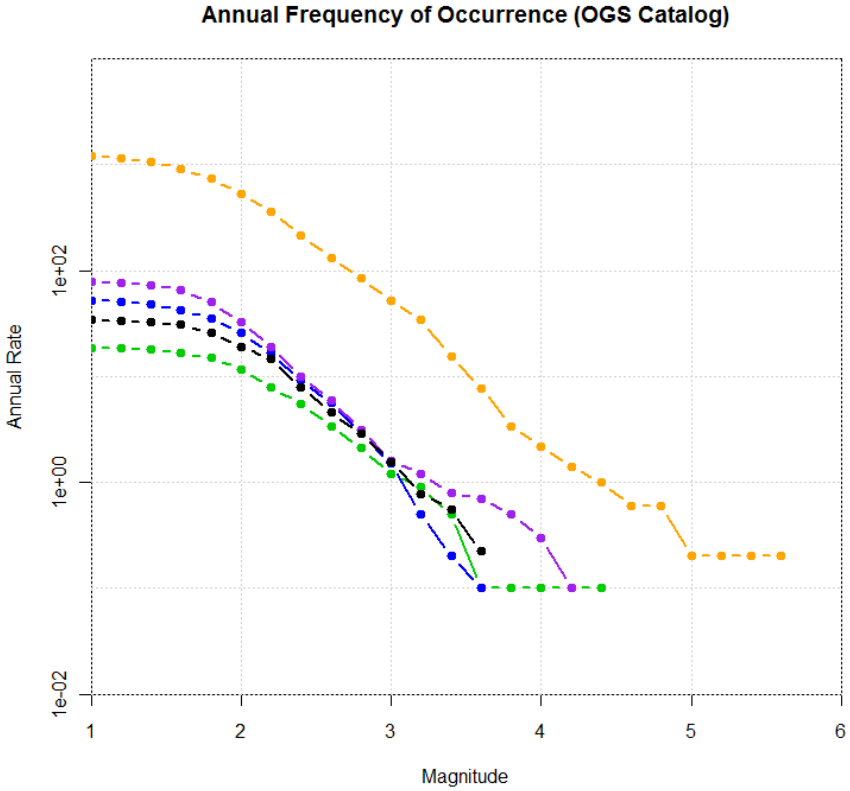
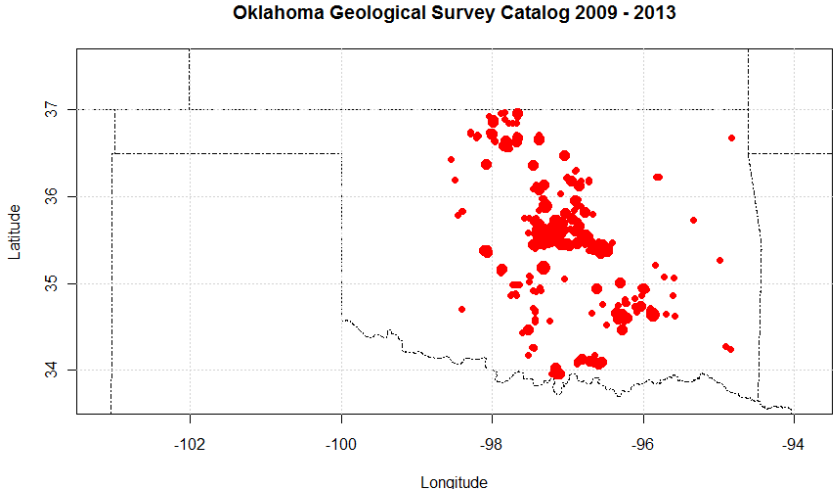
-94
Longitude

2009 - 2013


Annual Frequency of Occurrence (OGS Catalog)
Annual Rate
1e+02
1e+00
1e-02
1
2
3
4
5
6
Magnitude


Oklahoma Geological Survey Catalog 2009 - 2013
Latitude
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-102
-100
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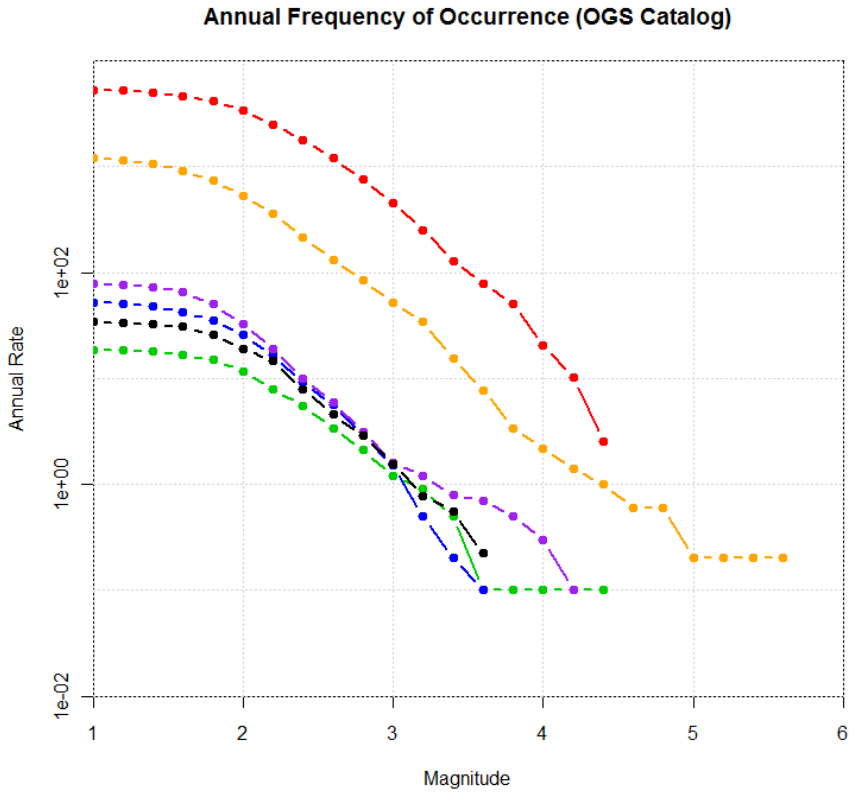
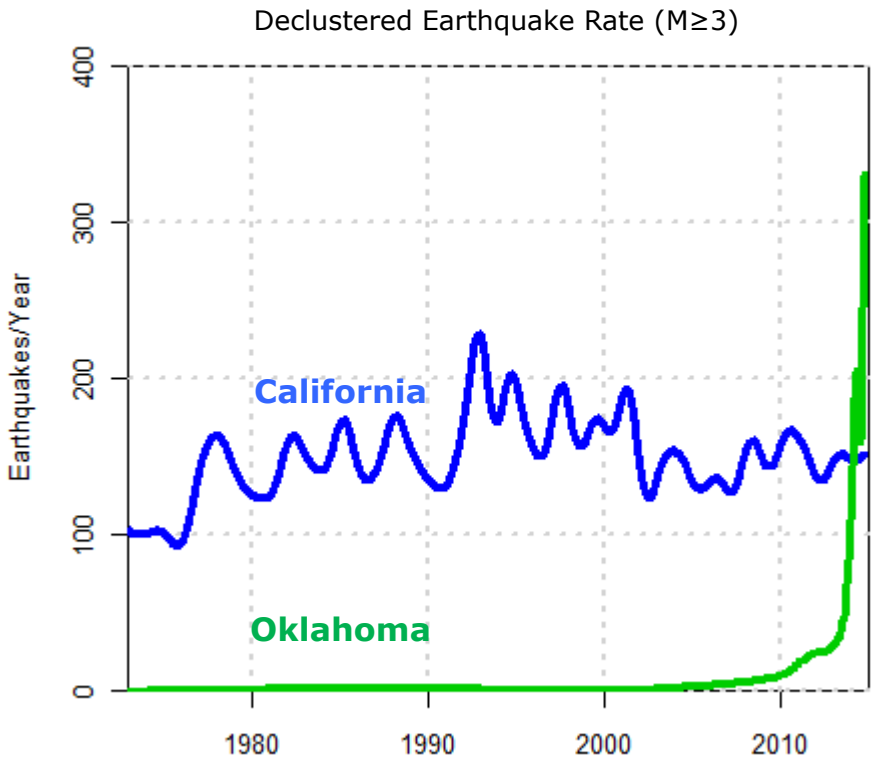
-96
-94
Longitude

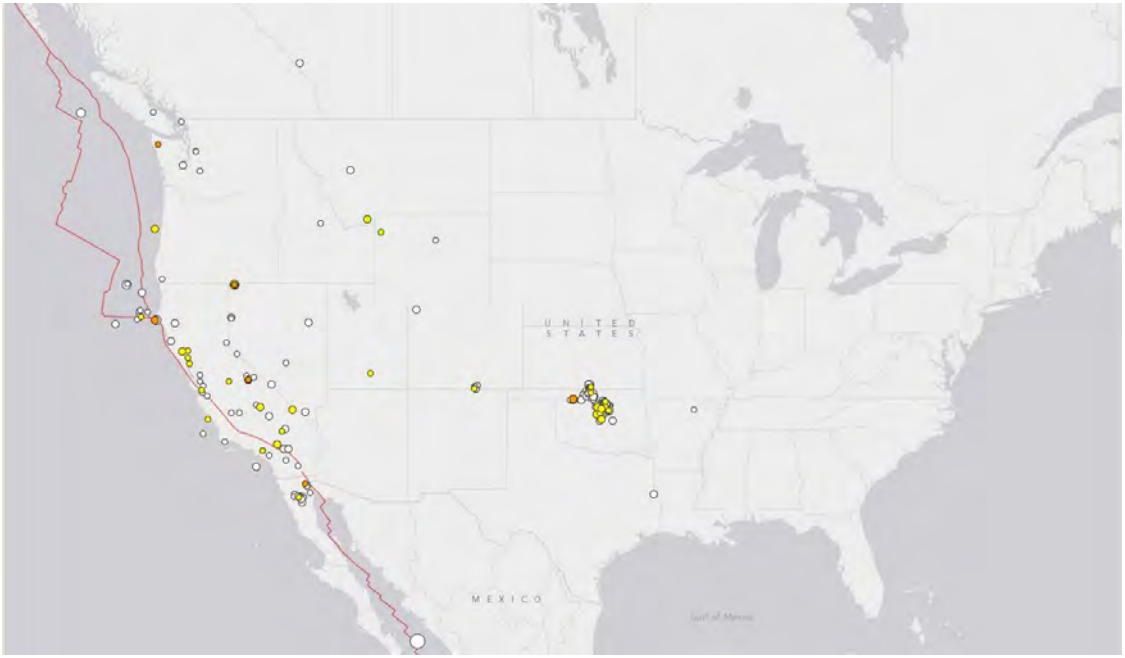
2014 through May



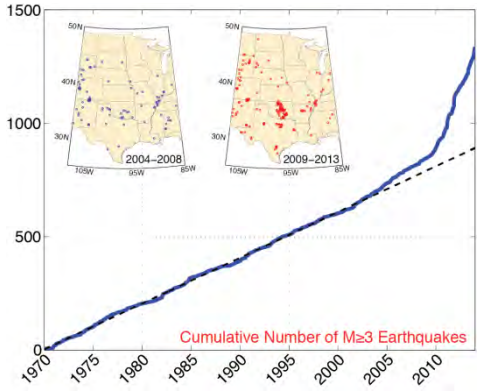


P(M≥5½) = 0.23 to 0.53
in the next 12 months

Compared with the 1970-2008
expectation of
P(M≥5½) = 0.003



Earthquakes for October, 2014
Magnitude ≥ 2.5



Higher rate of earthquakes implies higher hazard.

But how much higher?

And where has the hazard increased?

Thank You